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Mechanisms of long-term decay of tension stiffening

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Details of an extensive collaborative project to study tension stiffening have been recently published in a number of papers. Among other factors, the project investigated the loss of tension stiffening with time. It has been concluded that the reduction of tension stiffening to a constant long-term value is fairly rapid, being complete in 10–30 days. This paper explores the mechanisms that may operate to cause the reduction of tension stiffening with time. It is concluded that the loss is mainly attributed to cumulative damage resulting from either the formation of additional surface cracks or the formation or extension of internal cracks. It would appear that the final tension stiffening is only minimally dependent on concrete strength.

Introduction

An understanding of the interaction of reinforcement and the surrounding concrete is fundamental to the understanding of the behaviour of reinforced concrete. There are a number of aspects to this problem. These include an understanding of bond behaviour, of cracking behaviour and of the related problem of tension stiffening.

Traditionally, it is assumed in the design of reinforced concrete that concrete carries no tension. On this assumption, and assuming elastic behaviour of the steel and the concrete in compression, it is possible to calculate the stresses and strains in the concrete and the reinforcement and hence the deformations of the member. In practice, it is found that this procedure overestimates the deformations because the concrete in tension surrounding the reinforcement does, on average, carry some stress, even after cracking. This reduction in deformation or increase in stiffness is referred to as 'tension stiffening'. It is well known that tension stiffening reduces with time under load but there is minimal published information on the rate at which this takes place or the actual mechanisms that cause the reduction.

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Recently, two linked Engineering and Physical Sciences Research Council (EPSRC) grants were awarded—one to Durham University and one to the University of Leeds—to investigate tension stiffening and, in particular, the reduction in tension stiffening with time. In addition to the grants from the EPSRC, industrial contributions to the project, both financial and in-kind, were made by Arup Research and Development, Giffords, Cadogan Tietz and the Concrete Society. The experimental work carried out under these grants has enabled a very thorough study to be carried out into the behaviour of concrete in tension surrounding reinforcement.

A principal finding of the research has been that tension stiffening decays rapidly and will reach its long-term value of approximately half the short-term value in a period of less than 30 days and generally less than 20 days. The experimental results relating to this particular conclusion and its practical consequences have already been presented in earlier papers[1,2] and will not be discussed further here. In this paper, the results from the experimental work will be used to explore the behaviour of tension zones under long-term loading. In particular, in order to understand the process of the decay of tension stiffening, the results will be used to investigate the internal mechanisms occurring in the concrete surrounding the reinforcement. Details of the testing and instrumentation and the light shed on the short-term behaviour of tension members have been published elsewhere[1–4] so will not be described in detail in this paper.

Possible decay mechanisms

There are a number of mechanisms which may lead to a reduction in tension stiffening. Each of them will be considered, together with their likely effect, in this section.

Creep

Since the concrete surrounding the reinforcement is supporting tensile stresses, some degree of creep will occur. Studies have been carried out on creep in tension. This can differ significantly from creep in compression and the differences appear to depend on the nature of the curing regime (for more information see, for example, Neville and Brooks[5]). In practice, it is commonly assumed that creep in tension and compression are the same. In the case of tension stiffening, the problem is not straightforward since the strain in the reinforcement, and hence the strain imposed on the concrete, does not change greatly and therefore the issue is more one of relaxation than creep. These, however, are clearly complementary aspects of the same phenomenon. It should be noted that, while the compressive stresses in the compression zones of beams or slabs tend to be fairly high (several MPa), the average tensile stresses in the concrete surrounding the reinforcement are low (commonly of the order of 1 MPa in the short term). Hence, since creep is proportional to stress, the creep is relatively small. Furthermore, since the stress will reduce from the tensile strength of the concrete at initial cracking to a much lower level as cracking develops, the creep might be in a creep recovery mode and could be very small or even negative, depending on the rate of loading. Creep can be expected to be greater in members loaded at a level only just above the cracking load because the tensile stresses will be higher for such members than for members loaded to higher levels. Overall, the effects of creep are likely to be small and difficult to predict.

When looking at the experimentally obtained variation in concrete stress along a bar, the effect of creep would be expected to be a reduction in the peak stress and a decreasing reduction in stress as a crack is approached. The situation is illustrated schematically in Fig. 1(a). The change should not be sudden but should develop gradually over time.

Bond creep is occasionally mentioned as a mechanism of long-term deformation. The effect of such a phenomenon would be to reduce the gradient of the stress change adjacent to a crack. The effect would thus be indistinguishable from that shown in Fig. 1(a) for normal creep. Indeed, it can be seen that an unavoidable consequence of normal creep (or, more correctly, relaxation) will be a reduction in the shear stresses at the bar–concrete interface, which are commonly referred to as bond stresses.

Extension of internal cracks

Goto[6] carried out tests on tension specimens that showed that internal cracks developed from the ribs on deformed bars. By injecting red ink into a duct running parallel to a bar in a tension specimen and then cutting the specimen open, Goto was able to observe the pattern of internal cracking around a deformed bar. Otsuka and Osaka[7] carried out similar tests in an investigation of anchorage behaviour. Their tests suggest that the cracks are longest near the face of the concrete and reduce in length more or less linearly with increasing distance from the face. This led Beeby and Scott[2] to suggest that, on the formation of a primary crack, internal cracks formed as shown in Fig. 2. Since the steel strain is greater than the tensile strain capacity of the concrete over the whole transfer length (S_o), it was suggested by Beeby and Scott that the internal cracking formed over the whole of S_o almost instantaneously on the formation of the major surface cracks. With time, however, it seems likely that, although few new internal cracks should form, the existing internal cracks could lengthen, thus decreasing the stiffness of the connection between the bars and the surrounding concrete and hence decreasing the stress transferred to the concrete over the transfer length. The effect of this would be to reduce the stresses in the manner shown in Fig. 1(a). Inspection of the strain distribution will not therefore establish whether the change in stiffening is the result of creep or is the result of an increase in internal damage. A fuller analysis of the data will be needed to establish the relative importance of creep and increased internal damage owing to a gradual extension of internal cracking.

Shrinkage

Owing to the fact that the reinforcement does not shrink, the shrinkage of the concrete surrounding the reinforcement will be constrained and this will cause tension stresses to develop. Shrinkage is thus likely to lead to the formation of cracks under slightly lower loads than would be expected from the tensile strength of unrestrained concrete. This can conveniently be considered as causing a reduction in the effective tensile strength of the concrete. A simple analysis suggests the following relationship for the effect of shrinkage

$$f_{ct,eff} = f_{ct} - \sigma_{ct,sh} = \mathrm{f}_{ct} - E_s \rho \varepsilon_{sh}/(1 + \alpha_e \rho)$$

where

$f_{ct,eff}$ = the effective tensile strength of the concrete allowing for the effect of shrinkage

f_{ct} = the direct tensile strength of the concrete

$\sigma_{ct,sh}$ = the tensile stress developed in the concrete due to restraint of shrinkage by the reinforcement

ε_{sh} = the free shrinkage strain prior to cracking

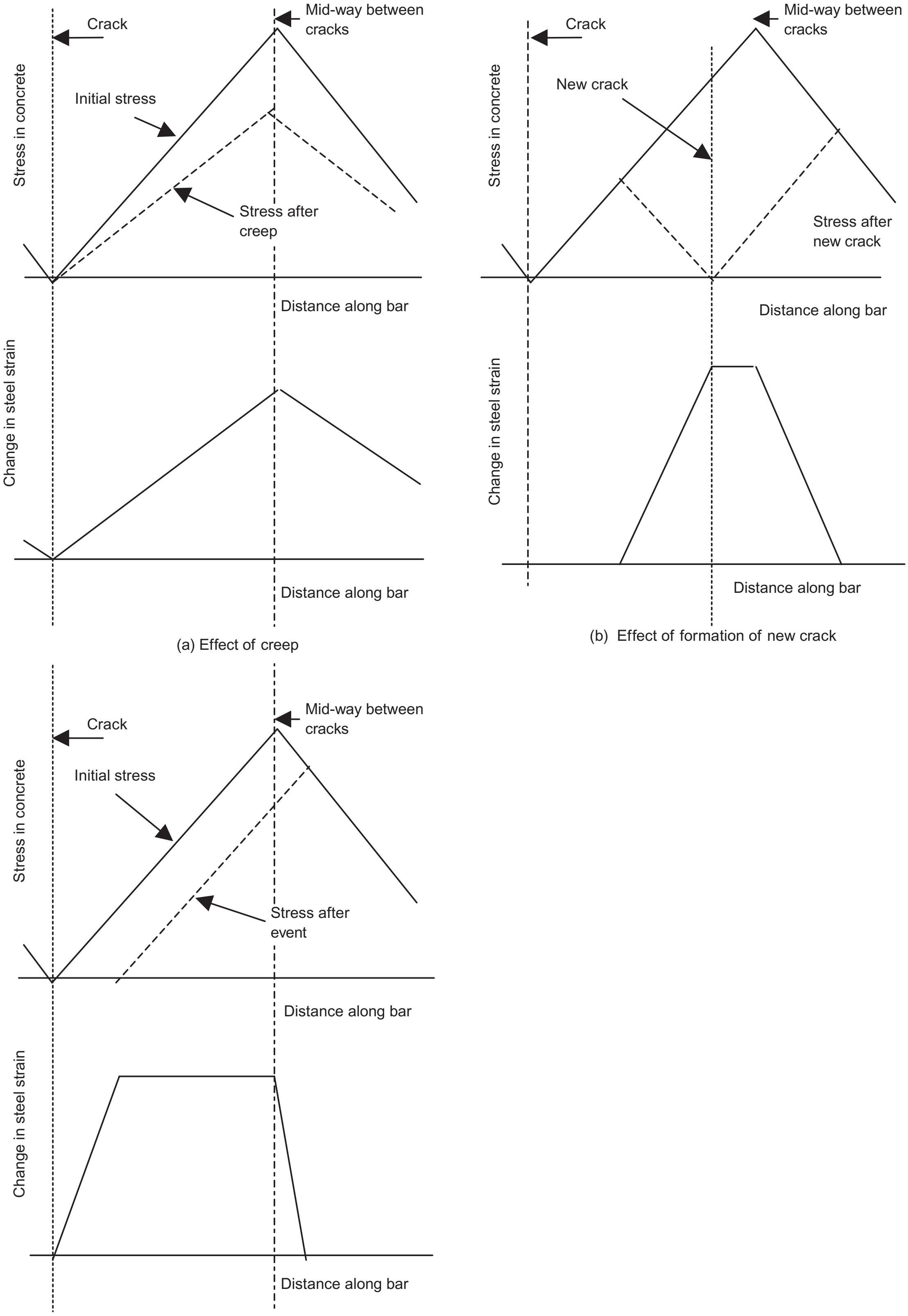

Fig. 1. Schematic diagram of effects of long-term phenomena on stresses and strains.

ρ = the reinforcement ratio related to the area of concrete immediately surrounding the reinforcement
α_e = the modular ratio, taking account of an effective modulus of elasticity of the concrete allowing for creep.

The formation of new surface cracks

The effect of the formation of a new crack is fairly obvious, but is illustrated schematically in Fig. 1(b). This change in stress distribution occurs suddenly. A

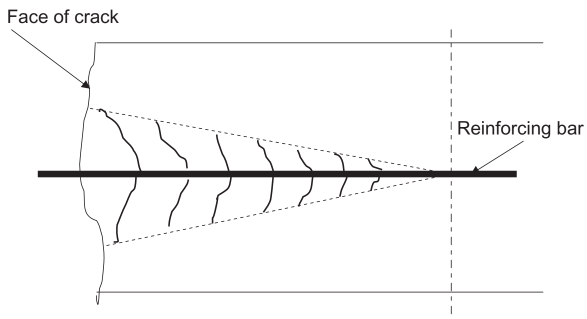

Fig. 2. Internal cracks as established by Goto[6] and Otsuka and Osaka[7]

less dramatic form of this type of event is where, initially, a surface crack does not extend around the full circumference of the tension zone but, with time or increase in loading, the crack lengthens. The effect of such an event is clearly concentrated at an existing crack location.

Sudden internal events

A variety of possibilities have been bundled together here as, since it is only the effects of the events and not the events themselves which can be observed, their cause cannot be established unequivocally, although their possible causes can be speculated upon. Their characteristic is that a sudden local reduction in tensile stress occurs without any new visible surface cracks appearing. In the testing carried out at Durham,[2] several forms of sudden internal event were identified.

Possibly the most dramatic event, although relatively rare, is a sudden failure adjacent to an existing crack. The effect of this is to detach a length of concrete adjacent to a crack from the reinforcement. This could be caused by a local total bond failure, but it seems more likely to be the result of an internal crack of the form identified by Goto[6] breaking through into the face of the crack. It can be seen from Fig. 2 that, if the crack nearest to the primary crack extends, it is likely to break through into the crack face. When this happens, the bar has become detached from the main body of the concrete surrounding the bar until beyond the first crack and there will thus be no transfer of stress between the bar and the concrete within this region. The effect of this type of event on the stress distribution is shown schematically in Fig. 1(c).

Sudden events do occur where the change in the stress distribution is of the type shown in Fig. 1(a). The cause of this change in stress distribution is not clear but might result from a general increase in length of the internal cracks illustrated in Fig. 2. The possible mechanism resulting in a sudden general increase in crack lengths could be as follows. With increasing deformation of the bar and hence the concrete surrounding the bar, the internal cracks shown in Fig. 2 are likely to lengthen. If such a crack does lengthen then the stiffness of the concrete cone bounded by the crack will reduce in stiffness and the load transferred by this cone between the bar and the concrete will reduce and the deformation of the cone will increase. The immediate result of this will be a transfer of force to the adjacent cones. The additional load on these is likely to result in them increasing in length and the process is repeated. Thus, the lengthening of any crack could easily set off a chain reaction of lengthening of all the other cracks and an overall reduction in stiffness of the concrete immediately surrounding the bar. This process probably generally happens gradually in general but, in this case, the results would be indistinguishable from creep. Owing to the variable nature of concrete, however, it seems possible that, on occasion, it happens suddenly.

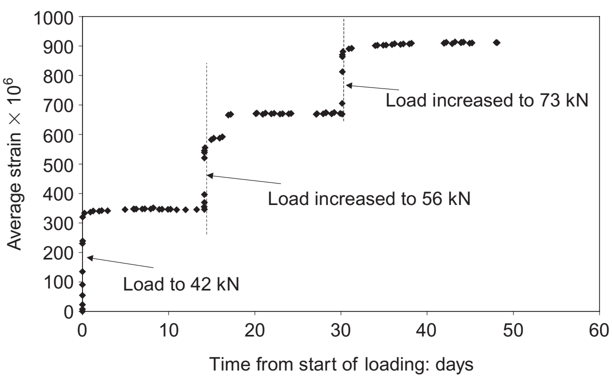

Fig. 3. Strain as a function of time for Durham specimen T20R3

Summary of test programme

The tests that will be considered in this paper were those carried out at the University of Durham since they provide the most detailed information on the long-term behaviour. The test procedure, instrumentation and rig design has been described fully elsewhere[4] and will not be described again here. All specimens were 1·2 m long and had a 120×120 mm cross-section reinforced with a single axially placed bar. Three concrete strengths were used: 25, 70 and 120 MPa. All the tests were carried out by loading the specimens in pure tension. Pairs of identical specimens were made and, while one of the specimens was loaded in a single increment to the maximum load, the other was loaded, generally, in three stages with the load being maintained constant for a considerable period of time at each stage. Details of the specimens are given in Table 1. In the nomenclature of the specimens, the bar size (T16 or T20) is given first, followed by either a letter R, indicating a specimen where the load was provided in three stages or a letter B, indicating that the load was applied in one single increment. The final number

Table 1. Details of specimens tested at Durham

Specimen number	Bar diameter: mm	Length of test: days	Concrete cube strength: MPa	Concrete indirect tensile strength: MPa	Load stages: loads in kN
T12B1	12	80	22·0	1·5	58
T12R1	12	80	22·0	1·5	43, 58
T16B1	16	127	23·5	1·9	74
T16R1	16	127	23·5	1·9	43, 57, 74
T20B1	20	133	33·5	2·5	73
T20R1	20	133	33·5	2·5	42, 59, 74
T16B2	16	50	69·0	3·5	72
T16R2	16	50	69·0	3·5	44, 58, 71
T20B2	20	56	89·0	3·4	73
T20R2	20	56	89·0	3·4	43, 58, 71
T16B3	16	119	123·5	5·5	78
T16R3	16	119	123·5	5·5	57, 71
T20B3	20	48	117·5	4·3	73
T20R3	20	48	117·5	4·3	43, 57, 71

indicates the concrete grade (1 indicates 25 MPa, 2 indicates 70 MPa and 3 indicates 120 MPa).

A study of a particular specimen under long-term loading

Having discussed the likely forms of event which could lead to long-term decay in tension stiffening, the means now exist for looking at the development of stresses and strains over time to establish the relative frequency of the various causes. This will be done for Specimen T20R3 from the Durham tests. This specimen was loaded in three stages and the load maintained constant for about 15 to 18 days at each load level. The overall behaviour can be seen from Fig. 3 which shows the average strain plotted against time for the whole test.

The major deformations are the instantaneous deformations occurring immediately upon application of the load. The deformations are summarised in Table 2 below. The total final deformation was 911×10^{-6} of which 68% was instantaneous and 32% long term. As discussed in earlier papers,[1–4] the evidence suggests that there would be little or no further long-term deformation. It will be seen that the situation is very different to creep where the long-term deformation is typically likely to be about double the short-term deformation.

It is now interesting to look at each of the three periods of constant load and attempt to identify the contributions of the various mechanisms leading to long-term deformation. As the free shinkage of the concrete was not measured, the effect of shrinkage occurring during the test cannot be isolated. Fig. 4 shows the strains occurring under a load of 43 kN plotted against the time from application of the 43 kN load. Log time has been used for convenience for the time axis. Between 15 and 45 min from the load being applied, a new crack formed and this resulted in a significant instantaneous increase in strain. Indeed, the formation of the new crack accounts for 70% of the deformation occurring after application of the load. The remaining 30% of the deformation is attributed to creep or a gradual increase in internal damage.

Figure 5 shows the development of the strain during the time that the load was held at 56 kN. In this case, the time scale is the log of the time from reaching a load of 56 kN. Inspection of the stress distributions

Table 2. Summary of deformations for specimen T20R3

Load: kN	Instantaneous deformation: strain $\times 10^6$	Long-term deformation: strain $\times 10^6$
42	230	116
56	193	130
72	195	47
Total	618	293

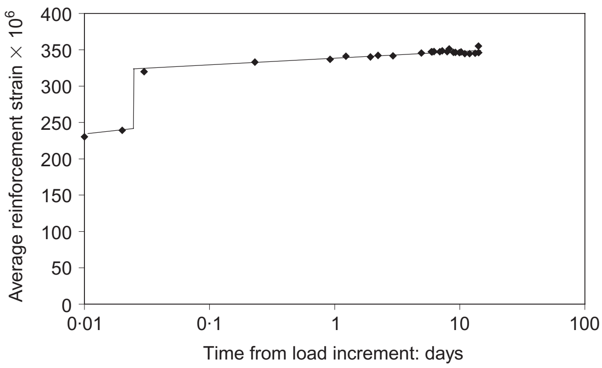

Fig. 4. Specimen T20R3—change in strain under load of 43 kN

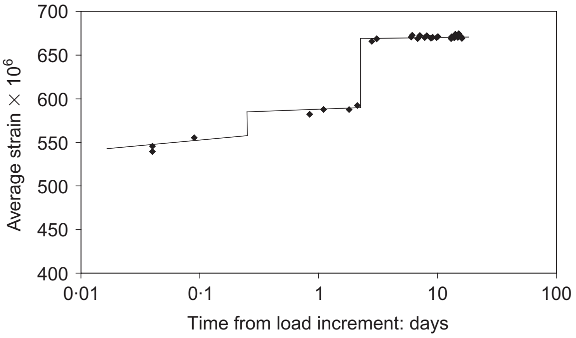

Fig. 5. Specimen T20R3—development of strain under load of 57 kN

shows that there are two step increases in strain; one occurring at about half a day from loading and another at 2·1 days from loading. The second event was the formation of a new surface crack but the earlier event cannot be related to any visible cracking. It is possible to see in more detail what is happening by plotting the change in strain between the sets of readings taken just before and just after the events. This has been done for the two events and the results are shown in Figs 6 and 7.

In the first event (Fig. 6), the change in strain occurs over a considerable length of the specimen on either side of an existing crack. This can only be the result of internal failure since no further surface crack occurred.

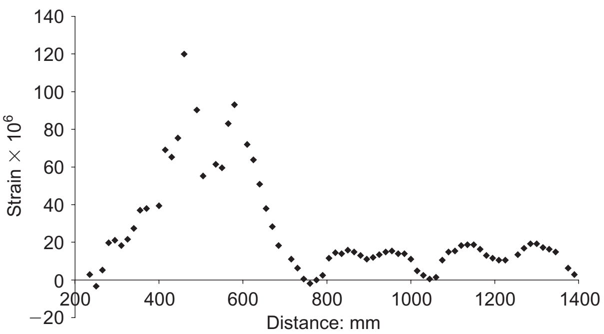

Fig. 6. Strain change at first event

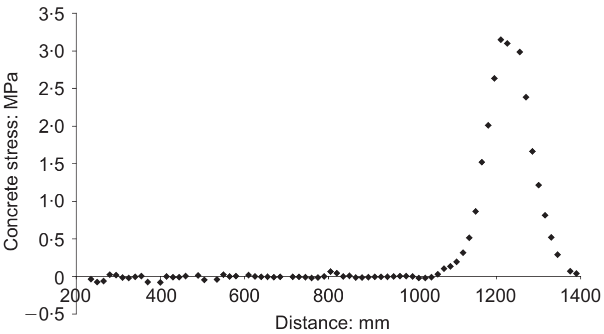

Fig. 7. Strain change at second event

The more or less constant small changes in strain in the region from about 750 mm to the right-hand end of the specimen are typical of creep. Since there is no stress in the concrete at the cracks there can be no creep at the crack locations but it can be expected to increase with increasing distance from the cracks. The results shown in Fig. 7 for the formation of a new surface crack are exactly what would be expected. Of the total deformation occurring while the load was held at 57 kN, the new crack accounted for 57%, the sudden internal failure for 27% and creep or gradual internal failure for 16%.

Figure 8 shows the development of strain over the period when the load was held at 71 kN. Fig. 9 shows the strain change along the length of the specimen over the full period that the load was held at 71 kN. In this case it will be seen that the increase in strain occurs almost entirely in the regions away from the cracks, suggesting that the increase in the average strain is almost entirely caused by creep or a gradual increase in internal damage. There were no new cracks and, had there been significant internal failure, this would have resulted in changes in strain which were greater close to the cracks and not, as in this case, greatest mid-way between the cracks.

Table 3 attempts to summarise the long-term results. Overall, it will be seen that two-thirds of the deforma-

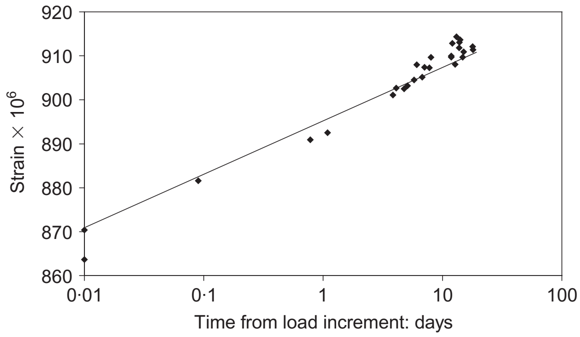

Fig. 8. Specimen T20R3—strain development under load of 71 kN

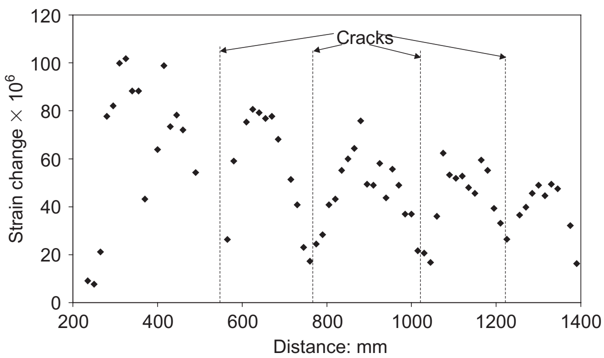

Fig. 9. Specimen T20R3—change in strains under load of 71 kN

Table 3. Summary of contributions to long-term deformation

Load: kN	Long-term strain change: $\times 10^6$	Percent of deformation owing to new cracks	Percent owing to sudden internal failure	Percent owing to creep or gradual internal failure
42	116	70	0	30
57	130	56	28	16
71	47	0	0	100
Total	293	53	13	34

tion were attributed to sudden failure events, which resulted in step changes in the deformation, and one third can be ascribed to creep or a gradual extension of the internal cracks.

Figure 10 shows the load–deformation response for specimen T20R3 compared with the response of the companion specimen T20B3. While T20R3 was loaded up in three stages with the load kept constant for 15 days at each stage, T20B3 was loaded up to the maximum load in a single step and then held at that load for 45 days. The final deformations of both specimens are very similar, suggesting that the final deformation is largely independent of the load history.

Analysis of the increase in deformation with time under the maximum load for specimen T20B3 shows that no extra cracks occurred during this period. The causes of the deformations are much less clear than in T20R3 but some idea of possible amount which may be ascribed to creep and internal failure may be obtained by considering the gradient of the plots of strain against log time. These should be the same for T20R3 and T29B3 since the specimens were cast at the same time and maintained in the same environment. This study suggests that gradual and sudden phenomena each contributed about 50% to the total long-term deformation.

Having discussed in detail the behaviour of a typical specimen, the results from all the tests will be summarised. This is done in Table 4.

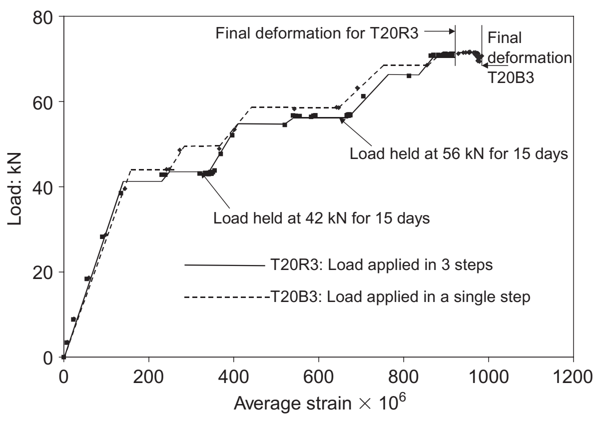

Fig. 10. Comparison of load–deformation responses of T20R3 and T20B3

Discussion of results

Figures 11 (a) and (b) show, for the specimens reinforced with 16 mm and 20 mm bars respectively, the instantaneous strain and the total strain. For the R series tests where loading was generally applied in three increments, the instantaneous strain is the sum of the instantaneous strains occurring on application of each load and similarly for the long-term strains. Two points are immediately discernable. First, the instantaneous strains where incremental loading was carried out are always significantly smaller than those obtained where the loading was all applied at one time. Second, despite this, the total strain is more or less the same regardless of the loading mode. This confirms the result illustrated in Fig. 10 for specimens T20R3 and T20B3. A further point, which is not quite so clear, is that concrete strength has little effect on the final deformation. The effect is actually rather less than the graphs indicate because the loading varied somewhat between specimens. Notably, specimens T20-3 were only loaded to 70·5 and 71 kN whereas T20-1 specimens were loaded to 74·5 and 74 kN and T20-2 to 72·5 and 72·8 kN. T16-3 specimens were loaded to rather higher loads than the other 1 mm reinforced specimens. No attempt has been made to correct for these minor loading differences.

Figures 12 (a) and (b) consider the long-term increments in strain. The graphs show the total long-term increments for the two forms of loading (solid lines) and the total increment assessed to have occurred as sudden events such as the formation of an additional crack (broken lines). It is interesting that for members reinforced with 16 mm bars, there is a clear increase in long-term deformation with increase in concrete strength. This is less clear for specimens reinforced with 20 mm bars for the highest strength but a general increase in long term deformation can still reasonably be postulated. It is also clear that the long-term deformations where the loading was applied in one increment were substantially smaller than those obtained where the load was applied in stages. The assessment of the increment owing to sudden events is somewhat subjective in some cases but the lines are believed to give a reasonable indication of behaviour. On average, sudden events contribute approximately 30% to the long-term deformation. This is somewhat less than for

Table 4. Summary of results for long-term tests

Specimen	Cube strength: MPa	Indirect tensile strength: MPa	Load: kN	Time from first loading: days	Instantaneous strain: $\times 10^6$	Long-term strain: $\times 10^6$	Total strain: $\times 10^6$
T16R1	23·5	1·9	43·0	41	733	32	765
			57·0	65	933	147	1080
			73·5	93	1245	254	1499
T16B1	23·5	1·9	74	126	1507	43	1550
T16R2	69·0	3·5	44	15	711	192	903
			58	50	950	271	1221
			70·5	50	1172	368	1540
T16B2	69·0	3·5	71·5	29	1492	98	1590
T16R3	123·5	5·5	61·0	28	659	232	891
			82·0	86	1236	499	1735
T16B3	123·5	5·5	78	86	1442	165	1607
T20R1	33·5	2·5	42·3	21	483	53	536
			59	46	671	122	793
			74·5	71	826	196	1022
T20B1	33·5	2·5	74	76	1050	47	1097
T20R2	88·8	3·4	42·5	21	464	49	513
			58·5	28	663	105	768
			72·5	35	811	295	1106
T20B2	89·0	3·4	72·8	50	1020	89	1109
T20R3	117·5	4·3	43·2	14	230	116	346
			57·0	30	423	246	669
			71·0	48	618	294	912
T20B3	117·5	4·3	70·5	48	901	75	976

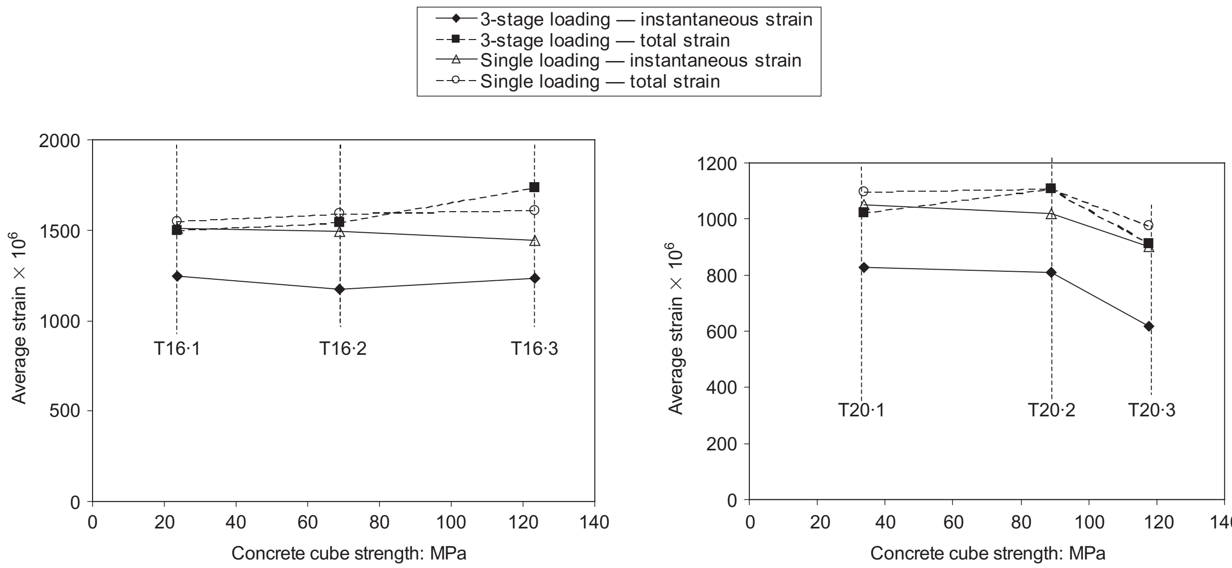

Fig. 11. Effect of cube strength on the instantaneous and total strains

specimen T20R3, which was considered in detail earlier.

There remains the problem of attempting to assess the relative importance of creep and a gradual increase in internal damage. There are two approaches to considering this question: the amount of creep that can be expected from current prediction methods for creep and a consideration of whether the results obtained for the gradual increase in deformation are consistent with expected creep behaviour.

Taking the first approach, the CEB Model Code 90 includes a method for the prediction of creep that is generally considered to be reasonable for creep in compression. This method, with some limited modifications, is included in Eurocode 2.[8] Neville and Brooks[5] state that the relationship between compression creep and tension creep is somewhat variable but, in some circumstances, tension creep can be up to double the compression creep under a numerically identical stress level. In the following, a worst case will be assumed

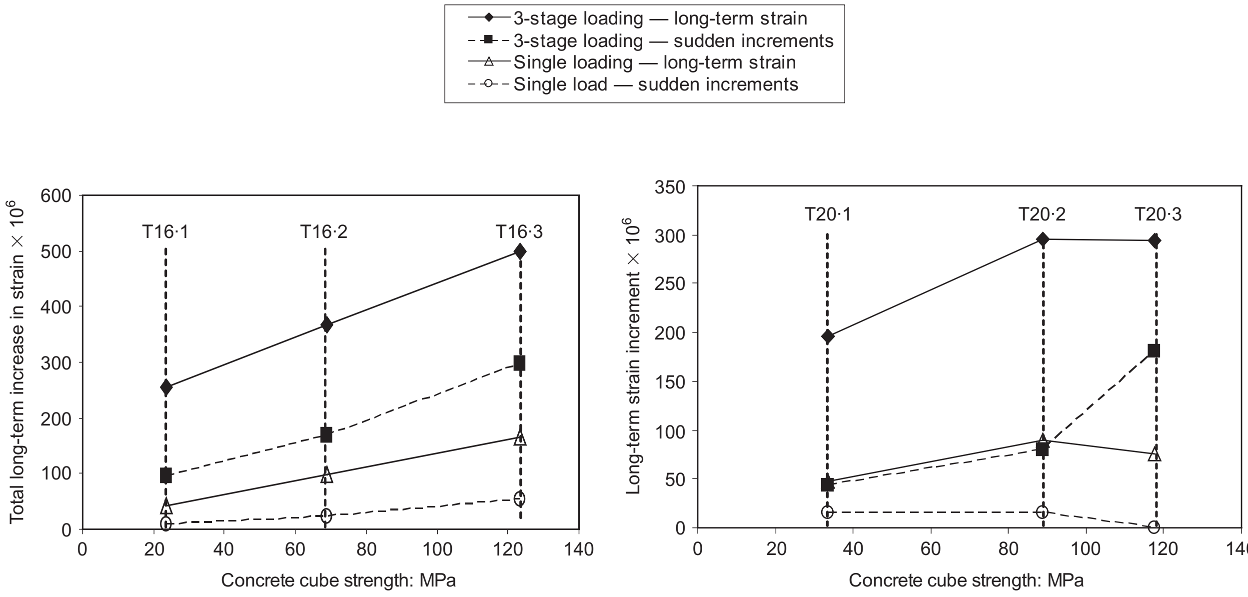

Fig. 12. Long-term increments in deformation as a function of cube strength

and the tension creep coefficient will be taken as twice the value calculated using the Eurocode 2 method for compression creep. The stress in the concrete over time has been calculated for all load stages in all specimens but, for the purposes of this brief study, an average stress will be used for each test. Table 5 gives the total long-term deformation and that part of the long-term deformation considered to be gradual at the end of each test together with the calculated deformation owing to creep. It will be seen that, except for the lowest-strength specimens where the load was applied in a single increment, creep is predicted to be able to account for only a very small portion of the long-term deformation.

The second approach is slightly more difficult to demonstrate owing to the relatively small long-term deformations. It will have been seen from the earlier study that the gradual component of the long-term deformation can be conveniently expressed as a straight line on a plot of deformation against log time. This suggests that the form of the relationship between gradual deformation and time for, for example specimen T16R2, is as sketched schematically in Fig. 13. At first glance it could be assumed that this is the form of relationship expected from creep where the load is applied in a number of stages. This is, however, misleading. Fig. 14 shows the variation in concrete stress over the whole period of the testing of T16R2. It will be seen that, although there are small local 'blips' in the tension stress at the time of application of each load increment, the concrete stress actually remains more or less constant over the test period at an average of about 0·45 MPa. Creep deformations under this constant stress would not be expected to be of the form shown

Table 5. Comparison of calculated effect of creep and gradual deformations

Specimen number	Concrete cube strength: MPa	Total long-term strain change: $\times 10^6$	Estimated gradual strain change: $\times 10^6$	Maximum estimate of calculated creep strain: $\times 10^6$
T16R1	23·5	254	160	62
T16B1	23·5	43	34	28
T20R1	33·5	196	153	44
T20B1	33·5	47	31	30
T16R2	69·0	368	201	28
T16B2	69·0	98	76	8
T20R2	89·0	295	215	34
T20B2	89·0	89	74	10
T16R3	123·5	499	201	40
T16B3	123·5	165	112	18
T20R3	117·5	294	113	30
T20B3	117·5	75	75	18

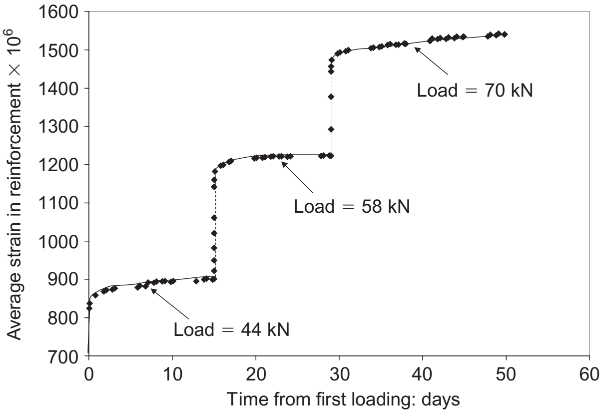

Fig. 13. Form of relationship between gradual strain increments and time for specimen T16R2

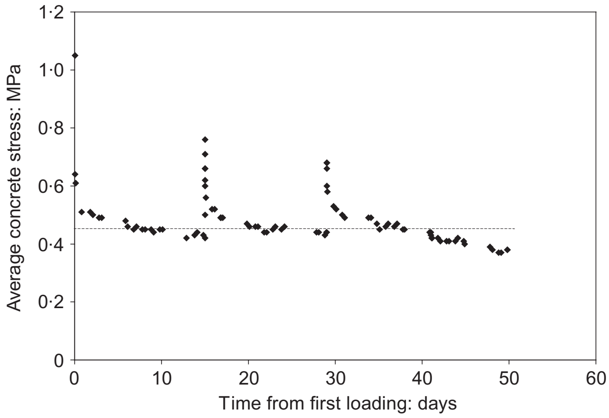

Fig. 14. Variation in concrete stress with time for specimen T16R2

in Fig. 13 since the increments in load do no more than cause a 'blip' in the stress and not an increase. The type of relationship obtained seems more consistent with a major change in the rate of change of deformation on the application of load to be the result of additional internal damage rather than creep which, by definition, is stress related. Studying these two approaches, it seems reasonable to conclude that the contribution of creep to the long-term deformation of tension zones is small and that the deformation is dominantly a result of cumulative damage of one form or another.

It has already been noted that in all cases the total final deformations of the two specimens making up any pair are very similar. The average difference is 6% with a maximum difference of 10%. There are, however, very significant differences in how this final value of deformation is reached. In all cases, the sum of the instantaneous deformations on applying each loading increment is smaller for the stepped loading regime than for the single loading while the sum of the long-term increments under constant loads is larger. The detailed study of the behaviour of T20R3 and T20B3 described above makes clear why this is so. Looking at Fig. 4, which shows the change in deformation in specimen T20R3 under the lowest load level of 43 kN, it will be seen that a new crack occurred within 1 h of the load being applied and that this made up a major part of the long-term deformation under this load. It is reasonable to assume that, had a slightly higher load been applied, the crack would have occurred during loading and hence would have been classified as part of the instantaneous deformation not the long-term deformation. A similar argument can be used for all the other instances of sudden failure events (new cracks or internal failures) occurring during the periods of constant load below the maximum. In T20B3, where the load was increased in one step up to the maximum, about the same total amount of deformation occurred owing to failure events as in T20R3 but all appear as part of the short-term deformation. Thus, calculation of short-term deformations and the establishment of the final deformation by adding a long-term increment to this, or by factoring the short-term deformation, is a somewhat dubious procedure. The values of the short-term and long-term deformations depend on just what cracks or internal failure events have occurred during the loading and what cracks and internal failure events occur during the period of constant loading. The way these events are distributed between short term and long term is a stochastic process depending on the variation of concrete strength along the length of the member and is not uniquely predictable. Since, however, the total amount of failure that occurs appears to be largely independent of the loading history, the final deformation appears to be calculable with much more reliability. This provides a strong argument for ignoring the short-term behaviour of tension zones and concentrating in practice on the prediction of only the long-term behaviour. It also casts doubt on the usefulness of methods where the short-term deformation is calculated and then multiplied by a factor to obtain a long-term deformation.

It has been suggested above that the major cause of the decrease in tension stiffening with time is an increase in cumulative damage. To some extent this is caused by the formation of further surface cracks but to a larger extent, this seems likely to be the result of internal phenomena. It is suggested that the most likely internal phenomena are related to internal cracking where there are three possibilities: increase in the number of internal cracks, increase in the length of internal cracks and breaking through of the internal cracks nearest to crack surfaces into the cracks. A possible cause of all these possible modes of increase in cumulative damage can be hypothesised. It is well known that both the tensile and compressive strength of concrete decrease with time under constant load. The reduction in tensile strength has been less fully investigated than that of compressive strength but some data, re-plotted from Comité Euro-International du Béton,[9] are presented in Fig. 15. It will be seen that the tensile strength appears to reduce by about 35% over a period of around 1 to 10 days, which is similar to the time during which tension stiffening is found to reduce. This suggests that the increase in cumulative damage and hence the loss of tension stiffening may simply be the result of a reduction in tensile strength of the concrete surrounding the reinforcement. Some confirmation of this can be obtained from inspection of current calculation methods for tension stiffening. For example, the calculation method given for deformations in Eurocode 2[8] would give, for the deformation of a member subjected to pure tension, the following relationship

$$\varepsilon_{\mathrm{sm}} = (1 - \zeta)\varepsilon_{\mathrm{s1}} + \zeta\varepsilon_{\mathrm{s2}}$$

where
ζ is given by $\zeta = 1 - \beta(N_{\mathrm{r}}/N)^2$
$\varepsilon_{\mathrm{s1}}$ is the strain in the reinforcement calculated assuming the section is uncracked
$\varepsilon_{\mathrm{s2}}$ is the strain in the reinforcement calculated on the assumption that the concrete carries no tension (i.e. the concrete is fully cracked)
N_{r} is the axial load which will just result in the tensile strength of the concrete to be reached
N is the axial load considered
β is a factor that takes account of the duration of loading. $\beta = 1$ for short-term loads and 0·5 for long-term loads.

It will be seen that the reduction of β from 1 to 0·5 would give the same result as reducing the tensile strength of the concrete, and hence N_{r}, by 30%. This is close to the reduction in strength shown in Fig. 15.

It has been suggested, though the evidence is not absolutely clear, that final deformation is largely independent of concrete strength. Rutner[10] has also come to this conclusion. It appears that this occurs because, although the short-term deformation may reduce with increase in tensile strength, the long-term deformation increases substantially with increase in concrete strength. This suggests that high-strength concrete suffers a greater loss of tensile strength with time under load than does normal strength concrete. More research is needed to confirm or disprove this. If tension stiffening is largely independent of concrete strength, this casts doubt on deformation prediction methods such as that in EC2[8] where the deformation is strongly dependent on the tensile strength of the concrete.

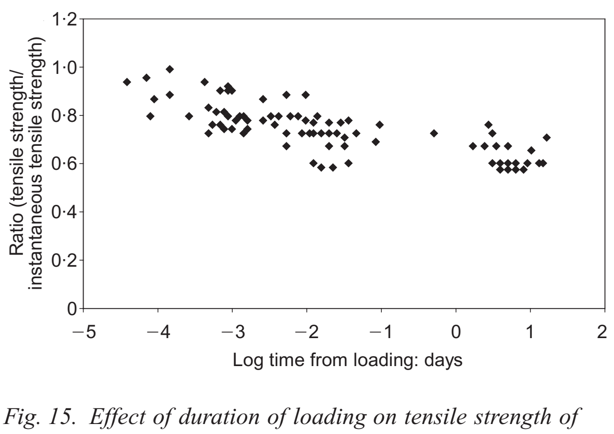

Fig. 15. Effect of duration of loading on tensile strength of concrete

Conclusions

(*a*) It has been demonstrated in previous papers that the loss of tension stiffening with time takes place relatively rapidly with the long-term final tension stiffening being reached within a period of 20 to 30 days.

(*b*) It is suggested in this paper that the major mechanism controlling the long-term loss of tension stiffening is the development with time of cumulative damage. This may be the formation or extension of existing surface cracks or the development or extension of internal cracks. Creep plays an insignificant part in the changes in tension stiffening with time.

(*c*) The final deformation of a tension member appears to be largely independent of load history and potentially more accurately determinable than the short-term deformation. The short-term deformation is heavily dependent on the precise state of cracking at the moment when the load is applied, which is highly unpredictable. The formation of cracking (or the development of cumulative damage) will have stabilised by the time that the long-term value of tension stiffening has been attained.

(*d*) It should be noted that the change in deformation owing to the loss of tension stiffening is relatively small compared with the initial deformation. This is not to be confused with the situation in more heavily reinforced flexural members where the long-term deformation is dominantly the result of creep in the compression zone, which can lead to large changes in deformation.

(*e*) It is suggested that the loss of tension stiffening with time is largely attributed to an increase in cumulative damage which, in turn, results from the reduction in tensile strength of concrete with time under load.

(*f*) There is evidence that the final tension stiffening may be largely independent of concrete strength. This, if confirmed by further research, may have significant practical consequences.

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References

1. Beeby A. W. and Scott R. H. *Tension stiffening of concrete—the behaviour of tension zones in reinforced concrete including time dependent effects*. The Concrete Society, Camberley, UK, 2002.
2. Beeby A. W. and Scott R. H. Cracking and deformation of axially reinforced members subjected to pure tension. *Magazine of Concrete Research*, 2005, **57**, No. 10, 611–621.
3. Beeby A. W. and Scott R. H. Insights into the cracking and tension stiffening behaviour of reinforced concrete tension members revealed by computer modelling. *Magazine of Concrete Research*, 2004, **56**, No. 3, 179–190.
4. Scott R. H. and Beeby A. W. Long term tension stiffening effects in concrete. *ACI Structures Journal*, 2005, **102**, No. 1, 1–9.
5. Neville A. M. and Brooks J. J. *Concrete Technology*. Longman, London, 1987.
6. Goto Y. Cracks formed in concrete around deformed tension bars. *Journal of the American Concrete Institute*, 1971, **68**, No. 4, 244–251.
7. Otsuka K. and Ozaka Y. Group effects on anchorage strength of deformed bars embedded in massive concrete block. *Proceedings of International Conference on Bond in Concrete – From Research to Practice*, Riga Technical University, Riga, October 1992.
8. Comité Européen de Normalisation. *Eurocode 2: Design of Concrete Structures – Part 1: General rules and rules for buildings, prEN 1992-1-1*. CEN, Brussels, April 2003.
9. Comité Euro-international du Beton. Serviceability models—behaviour and modelling in serviceability limit states including repeated and sustained loads: progress report. *Bulletin d'Information* No. 235, CEB, Paris, 1997.
10. Rutner M. The long term tension stiffening in composite bridge construction. *Beitrage aus dem Konstructiven Ingenieurbau*, Dissertation, Technische Universitat Munchen. Report 8/2003, p.173.

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